EFFECT OF FIBER ORIENTATION ON THE BEHAVIOR OF CFRP CONFINED CONCRETE CYLINDERS

Ahmed, Sulaiman
Master's candidate, University of Ottawa

Husham Almansour
Associate Research Officer, National Research Council of Canada

Hassan Aoude
Associate Professor, University of Ottawa

ABSTRACT

This paper presents the results of an ongoing experimental investigation examining the effect of fiber orientation and stacking sequence on the behavior of FRP-confined concrete. As part of the experimental study, 100 mm x 200 mm concrete cylinders were jacketed with carbon fiber reinforced polymer (CFRP) sheets and tested under pure axial compressive loading. The specimens were confined using various CFRP stacking sequences, with fibers oriented at 0º, 90º, and ±45º. Furthermore, within each stacking sequence, the numbers of layers was varied from 4 to 8 to examine the effect of number of plies on the behavior of the FRP-confined concrete cylinders. In addition, the research program included a companion set of CFRP coupons made from CFRP laminates having the same properties as the CFRP jackets used in the cylinder series. The preliminary results show that parameters such as fiber orientation, stacking sequence, and number of confinement layers have a direct impact on the strength, ductility and stress-strain behavior of CFRP confined concrete.

Keywords: - CFRP; Confinement; Columns, Fiber Orientation; Number of Layers.

1. INTRODUCTION

In the past three decades the popularity of fiber reinforced polymers (FRP) has increased in civil engineering applications due to their favorable properties which include: high strength-to-weight ratio, corrosion resistance, and high versatility which allows for ease of construction. In the case of reinforced concrete columns, application of externally-bonded FRP jacketing results in significant enhancement in strength and overall energy-dissipation capacity due to the ability of FRP to enhance confinement of the concrete cross-section (Sheikh et al. 2007). Over the years, a large number of studies have been conducted to examine the behavior of FRP-confined concrete, ranging from a large number of studies on small-scale cylinders as well as larger-scale reinforced concrete columns. The research has allowed for the development of numerous FRP confinement models and the development of design guidelines in codes of practice such as the Canadian CSA S806 Standard (Design and construction of building structures with fiber-reinforced polymers) (CSA, 2012). Most of these models and design equations have been developed based on data from cylinders and columns confined with unidirectional FRP oriented in the hoop direction. There is a need for further data to examine the effect of fiber orientation and stacking sequence on the stress-strain behaviour of FRP-confined concrete. This data is necessary to calibrate existing confinement models and code equations for columns confined with FRP having varying fiber orientations and stacking sequences.

Table 1: Summary of studies in the literature examining effect of FRP fiber orientation

Author	Type of test	Parameters	Main conclusions
Rajappa (2004)	Cylinders, coupons	• Concrete strength • Size effect • Number of layers • Fiber orientation	• Increase in peak stress more pronounced in specimens with lower concrete strength. • Increase in peak stress higher in smaller size specimens, opposite results obtained in the case of increase in strain. • Specimens with greater number of layers showed greater increase in strength and stiffness. • Specimens with 45º fibers showed relatively low increase in strength compared to those with hoop fibers.
Au and Buyukozturk (2005)	Cylinders	• Stacking sequence • Fiber orientation	• Specimens with equal number of layers but different layups showed different failure modes. • Brittle failure observed in specimens with hoop fibers, while ductile failure in specimens with angular fibers.
Li et al. (2005)	Cylinders, coupons	• Fiber orientation • Number of layers	• Fiber orientation & jacket thickness have influence on stress-strain behavior, strength, ductility & failure mode. • Specimens with confinement ratio smaller than 0.07 showed behavior similar to those of unconfined concrete.
Hong and Kim (2004)	Cylinders	• Cross-section shape • Winding angle • Number of layers	• Increase in stress and strain is more pronounced in circular specimens when compared to specimens with square cross-section. • Increase in stress is higher in specimens with fiber orientation close to hoop direction. • Both strength and stiffness increased proportionally with number of layers.
Vincent and Ozbakkalogl u (2013)	Cylinders	• Fiber orientation • Concrete strength • FRP tubes vs. wrap	• Specimens with hoop direction fiber displayed a greater increase in stress compare to those with fibers oriented at 45^0 or 60^0. Specimens with fibers in angular directions showed more ductile behavior compared to specimens with hoop direction fibers. • The increase in stress and strain was more pronounced in specimens with lower unconfined concrete strength. • No significant difference was observed in specimens confined with external FRP sheets and FRP tubes.
Parretti and Nanni (2002)	Columns	• Cross section shape • Fiber orientation	• Circular specimens with fibers in hoop direction showed sudden failure, while specimens with 45^0 fibers showed ductile response. • Rectangular specimens confined with fibers in 45^0 showed the best performance in the case of increase in ductility.
Hadi and Le (2014)	Columns, coupons	• Fiber orientation	• Better performance achieved from vertical and angular fibers as load eccentricity was increased.
Fam and Rizkalla (2001)	Conc. filled GFRP tubes	• Stacking sequence • Fiber orientation & loading condition • Size of core area	• Aligning fibers as closely as possible to hoop direction in GFRP tubes results in enhanced strength & stiffness • Aligning fibers in axial direction reduces strength and stiffness for the same number of FRP layers which is attributed to Poisson's ratio effect

A limited number of studies have examined the effect of FRP fiber orientation on the behaviour of FRP-confined concrete (some of these studies are summarized in Table 1). Sadeghian et al. (2009) examined the effect of fiber orientation by testing a series of CFRP coupons having different fiber configurations. A total of 24 coupon specimens (cross-section of 30 x 350mm) were tested under axial tension load. A total of eight wrap configurations were prepared from fibers oriented at 0^0, $\pm 45^0$ and 90^0, with the number of layers varying from 1 to 4 layers. The increase in the number of CFRP layers having the same orientation enhanced the stiffness and maximum load capacity of the coupons, while the maximum elongation remained relatively unchanged. Coupons with fibers oriented at 0^0 showed linear-elastic behaviour, with brittle rupture at failure. Coupons with a CFRP fiber orientation of $\pm 45^0$ showed nonlinear behavior and more ductile failure response. As the fiber angle approached 90^0, the ultimate strength of the FRP coupons reduced substantially. In a follow-up study, Sadeghian et al. (2010) tested a companion series of 30 cylinders having dimensions of 150 x 300 mm. The series including various stacking sequences with fibers oriented in the longitudinal (90º), transverse (0º) and diagonal directions (±45º), while the number of layers was varied between 1 and 4. Specimens with FRP sheets in the hoop direction (0^0) showed a significant increase in ultimate strength and ultimate strain when compared to the unconfined specimens. Specimens with FRP oriented in the longitudinal direction (90^0) did not show an increase in strength or ductility. However, when combined with FRP sheets at 0^0, the behavior of the specimens became similar to that of specimens with specimens having FRP fibers oriented in the hoop direction. Specimens confined with 4 layers of angled FRP ($\pm 45^0$) demonstrated an effective enhancement in ductility (with a ductility increase factor of 10) compared to unconfined cylinders, while specimens confined with 4 layers of 0^0 FRP sheets had a ductility increase factor of 8. Specimens confined with a combination of FRP sheets with fibers oriented in transverse and angled directions (0^0 and $\pm 45^0$) behaved in a similar fashion to cylinders confined purely with FRP in the transverse (0^0) direction. Fam and Rizkalla (2001) have studied the effect of fiber orientation in concrete-filled GFRP tubes and have found that aligning fibers as closely as possible to the hoop direction results in enhanced strength & stiffness when compared to fibres aligned in the axial direction. The result was attributed to Poisson's ratio effect, where the ratio is considerably higher than that of the concrete core when fibres are aligned in the axial direction, which reduces confinement efficiency. A summary of other studies in the literature along with conclusions are presented in Table 1.

2. EXPERIMENTAL PROGRAM

2.1 Details of the specimens

A total of 26 concrete wrapped cylinders and 5 unwrapped control specimens, were tested under uniaxial compression to failure. Variables considered in this study include: CFRP fiber orientation, CFRP stacking sequence (lay-up) and number of CFRP layers. Specimens were batched into 5 groups, namely, Groups 0 (control), 1, 2, 3, and 4 based on their fiber orientation and stacking sequences. Each stacking sequence had varying combinations and orientations (0˚, 90˚, ±45˚) of unidirectional (UD) and woven (W) ±45 CFRP. The test matrix is presented in Table 2. A total of 4 or 5 replicates were considered for each configuration.

Table 2**:** Test matrix

Series	Orientation	# of specimens	# of layers	Stacking sequence
0	Control	5	Control	Control
1	$UD[0^\circ]_4$	5	4	(0)-(0)-(0)-(0)
	$UD[0^\circ]_8$	5	8	(0)-(0)-(0)-(0)-(0)-(0)-(0)-(0)
2	$UD[90^\circ]W[\pm45^\circ]_2UD[0^\circ]$	4	4	(90)-(±45)-(±45)-(0)
	$UD[90^\circ]_2W[\pm45^\circ]_4UD[0^\circ]_2$	4	8	(90)-(90)-(±45)-(±45)-(±45)-(±45)-(0)-(0)
3	$W[\pm45^\circ]_2UD[0^\circ]_2$	4	4	(±45)-(±45)-(0)-(0)
4	$W[\pm45^\circ]_4$	4	4	(±45)-(±45)-(±45)-(±45)

2.2 Material properties

2.2.1 Concrete

Concrete of a relatively low compressive strength was used to fabricate the cylinders. The concrete, which had a specified strength of 25 MPa, was provided by a local ready-mix company; the mix proportions are shown in Table: 3. The concrete used commercially available Type I Portland Cement; 14 mm maximum size crushed limestone aggregate complying with ASTM C33-2013; sand conforming to the graduation requirement of ASTM C33-2013; and did not contain any dry or liquid admixtures. Standard concrete cylindrical specimens with dimensions (d x h) of 100 x 200 mm were used to determine the average strength of the concrete at 28 days and at 335 days which were found to be 30.78 MPa and 43 MPa.

2.2.2 Fiber Reinforced Polymer (FRP)

Two types of carbon fiber reinforced polymer (CFRP) fabric, with (1) unidirectional CFRP fibers (UD) and (2) woven ±45 CFRP fibers (W), were used in the experimental program. The unidirectional fabric consists of concentrated fibers at 0^0 with sparsely spaced fibers at 90^0 for linking (at a warp-weft ratio of 97%-3%), and has a nominal thickness of 0.34 mm/ply with a wet lay-up thickness of 0.7 mm/ply. The woven ±45 CFRP consists of 2:2 twill fabric with fibers aligned in $\pm45^0$ (at a warp-weft ratio of 50%-50%), and has a nominal thickness of 0.2 mm/ply with a wet lay-up thickness of 0.38 mm/ply. The stress-strain properties of the composite layups used to wrap the cylinders were determined experimentally by testing coupons in accordance to ASTM D3039/D3039M Standard. The epoxy consisted of *ProBuild MM55538* epoxy resin and *ProBuild MM55729* hardener at a ratio of 3:1 by weight, and was mixed manually for about 1 minute before saturating the CFRP fabric. According to the manufacturer, the mixed epoxy has a working life of about 30 minutes at 25 ^{0}C. This guideline was followed during the lay-up process of all CFRP-confined cylinder samples.

Table: 3 Concrete mix design

Materials	Mass (kg/m³)	Weight fraction (in terms of Cement)
Cement	256	1
Water	128	0.5
Sand	781	3.0
Aggregate	1077	4.2

2.3 Specimen preparation

Before wrapping, the concrete cylinders were ground flat at both ends using a cylinder grinder to ensure a smooth and uniform test surface for loading. The sheets were applied to the concrete surface by the wet layup method (Figure 3: Ductility and energy absorption capacity factors definition
). As noted previously the epoxy-resin ratio was 1:3. All cylinders were wrapped over their entire height and the CFRP plies were extended as close as possible to the ends of the cylinders to minimize the likelihood of premature failure of the unconfined concrete at the specimen ends. An overlap of 70 mm was used in between each layer of CFRP to prevent de-bonding during testing. In order to gain further understanding on the effect of FRP stacking sequence on laminate behavior, a set of CFRP coupons with same lay-ups considered for cylinders were casted and tested under axial tension.

Figure 1: Lay-up procedure

2.4 Instrumentation and test set-up

The specimens were tested using an *Instron SATEC* 2000 KN universal testing machine (see Figure 2) at the National Research Council of Canada (NRC). All specimens were tested at an age of 335 days. Since explosive and brittle failures were expected, the cylinder specimens were tested without external LVDTs or extensometers (see Figure 2). The axial strains on the specimens were obtained by adjusting the displacements recorded by the machine test frame using a calibration equation determined from previous testing at the NRC.

Figure 2: Typical explosive failure of CFRP Confined Specimens and test set-up

4. TEST RESULTS

The effect of the test variables on the behavior of the CFRP confined concrete cylinders is examined by comparing the stress-strain response of the specimens. In addition to comparing the relative increase in peak stress $\frac{f'_{cc}}{f_{co}}$ and strain $\frac{\varepsilon'_{cc}}{\varepsilon_{co}}$, various quantitative indicators related to strength, ductility and toughness as defined by Cui and Sheikh (2010) are also compared. These include: a strength enhancement effectiveness factor (k_1), a ductility factor (μ_{cu}), an energy absorption capacity factor (e_{cu}), and a work index (w_{cu}).

4.1 Stress-strain parameters

4.1.1 Strength effectiveness factor (k_1)

The strength enhancement factor (k_1) is calculated using the expression shown in [1] which consists of the ratio of maximum increase in concrete stress and the maximum confining pressure of the FRP jacket.

[1] $k_1 = (f'_{cc} - f_{co})/f_l$

Where f'_{cc}= peak confined concrete stress, taken as the greater of f_{co} (peak stress of unconfined concrete); f_l = maximum confining pressure provided by the FRP jacket; where $f_l = 2.f_{FRP}.n_{FRP}/D$ and where n_{FRP} = number of FRP layers; f_{FRP} = tensile strength of FRP material in fiber direction (with units of N/mm/layer), as obtained from the tension coupon tests, and D = diameter of the specimen.

4.1.2 Ductility factor (μcu)

The ductility factor is defined as the ratio of the rupture strain and the axial strain corresponding to the maximum confined concrete stress on the initial tangent and is calculated using the expression shown in [2]:

[2] $\mu_{cu} = \varepsilon'_{cc}/\varepsilon_1$

Where ε'_{cc}= axial strain corresponding to rupture of the FRP jacket and ε_1 = axial strain corresponding to the maximum confined concrete stress on the initial tangent E_t (see Figure 3a)

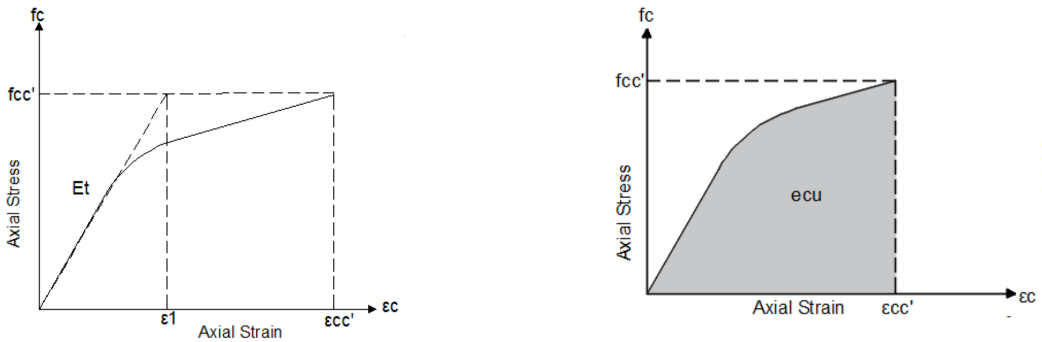
4.1.3 Energy absorption capacity factor (e_{cu})

Energy absorption capacity is defined as the area under the stress-strain curve up to the rupture of FRP jacket and is graphically presented in Figure 3b.

4.1.4 Work index ($\boldsymbol{w_{cu}}$)

The last indicator that is used to evaluate stress-strain response is the Work index, a dimensionless parameter which is calculated by normalizing the energy absorption capacity as shown in
[3]:

$$w_{cu} = e_{cu}/(f'_{cc}\ x\ \varepsilon_1) \qquad [3]$$



a) Definition of the ductility factor

b) Definition of energy absorption capacity

Figure 3: Ductility and energy absorption capacity factors definition

4.2 Effect of fiber orientation and stacking sequence

4.2.1 Coupons

Figure 4a shows the effect of stacking sequence on the stress-strain behavior of flat coupons having 4 layers of CFRP sheets. It is clear that the highest stiffness and strength was recorded for Series 1 which had fibers in UD [0°], parallel to the loading axis, while the maximum ductility was achieved for Series 4 which had fibers woven in angular direction (+/- 45°). Linear-elastic behavior is obvious in those series with unidirectional UD [0°] fibers. On the other hand, non-linear behavior was observed in the coupons with fibers woven in 45° angular directions. Series 2 and 3 showed a compromise of both behaviors, although the unidirectional fibers tend to dominate response. For example, coupons with combination of UD [0°] and W[±45˚] showed limited nonlinear behavior up to the rupture strength of angular fibers followed by linear behavior due to unidirectional direction fibers until final rupture of the coupon. Post failure photos from coupons are presented in Figure 5. No significant difference is observed in the failure photos, nonetheless more brittle failures occurred in those specimens with larger amounts of unidirectional fibers parallel to the loading axis. Maximum stress was obtained by coupons with UD [0°] CFRP sheets which was 961 MPa, while minimum stress was achieved by coupons W[±45˚] CFRP sheets which was 132 MPa. The opposite trend is observed in the case of rupture strain, where the W[±45˚] series shows the largest strain capacity. Series 2 and 3 showed stress-strain behavior in between these extremes.

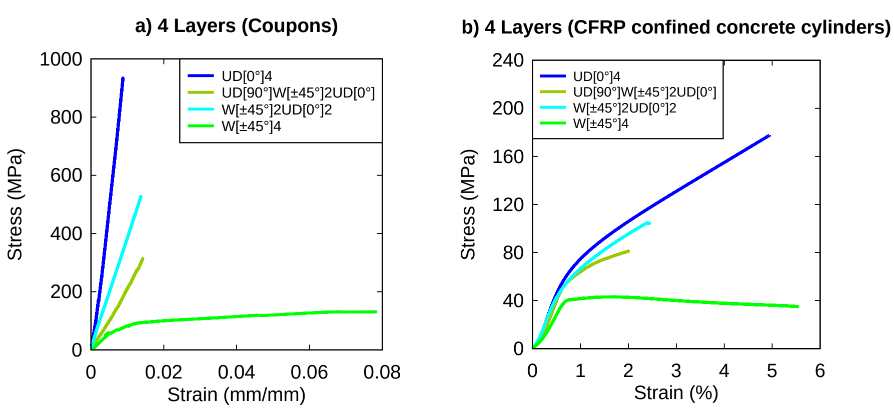


Figure 4: Effect of stacking sequence on stress-strain behavior of CFRP coupons and concrete cylinders

4.2.2 Cylinders

The effect of fiber orientation on the behaviour of FRP-confined concrete can be examined by comparing the stress-strain behaviour of the cylinders with 4 layers of CFRP. As shown in Figure 4, the stress-strain response of the series 1 specimen which was confined with UD [0º] CFRP shows an initially steep parabolic ascending branch followed by a quasi-linear second branch up to failure, with large increases in both maximum stress and strain when compared to the plain unconfined concrete. The series 4 specimen, which was confined with W[±45˚] CFRP, shows an initial ascending parabolic branch with only a nominal increase in peak stress, followed by a plastic plateau and large strain capacity before failure. Specimens in Series 2 and 3 show a hybrid of the responses observed in series 1 and 4, with an initially parabolic ascending branch followed by a second branch with relatively lower stiffness when compared to Series 1, although the stress-strain response seems to be dominated by the UD [0º] fibres. It is noted that the transition point between the two branches is somewhat more rounded when compared to Series 1. Fam and Rizkalla (2001) have shown that orienting fibres away from the hoop direction can result in a reduction of confinement efficiency due to Poisson's ratio effect, where the FRP shell expands at a higher rate when compared to the concrete core, and this effect warrants further study for concrete confined with complex FRP stacking sequences.

Table 4 reports the average stress-strain parameter (as defined in section 4.1) for the various specimens tested in this study. It can be observed that the Series 1 specimens, which were confined purely in the hoop direction (0°), experienced the larger strength increase ratio (f'_{cc}/f_{co}) when compared to other series. The strength increase ratio (f'_{cc}/f_{co}) for specimens with 4 plies of CFRP were determined as 313.4%, 88.9%, 141.9%, and 1.02% for the UD[0˚] (Series 1), UD[90˚]W[±45˚]$_2$UD[0˚] (Series 2), W[±45˚]$_2$UD[0˚]$_2$ (Series 3), and W[±45˚]$_4$ (Series 4) configurations, respectively. It can be seen that the largest values are reported for specimens with a greater amount of UD[0˚] sheets. When considering all specimens, the maximum increase in strain ($\varepsilon'_{cc}/\varepsilon_{co}$) was obtained for specimens confined with the woven angular fibers (Series 4), with an average strain increase ratio of 1568%. Fiber orientation did not have a significant impact on the strength effectiveness factor (k_1) which fluctuated around between 1.5 and 2, except for CFRP jackets placed in W [±45˚] which had a (k_1) value less than 1 because of a small gain in strength. The influence of orientation on energy absorption capacity factor (e_{cu}) was found to be largest for the UD [0°] pattern, with the following sequence of decreasing energy absorption for the remaining series: UD [0˚] > W[±45˚]$_2$UD[0˚]$_2$ > W [±45˚]$_4$ > UD[90˚]W[±45˚]$_2$UD[0˚] . Maximum values of 13.1 and 9.2 for the ductility factor (μ_{cu}) and the work index (w_{cu}), were achieved for specimens in Series 2 (UD[90˚]W[±45˚]$_2$UD[0˚]). This layup sequence showed moderate increase in stress and increase in strain, with additional benefits in terms of failure.

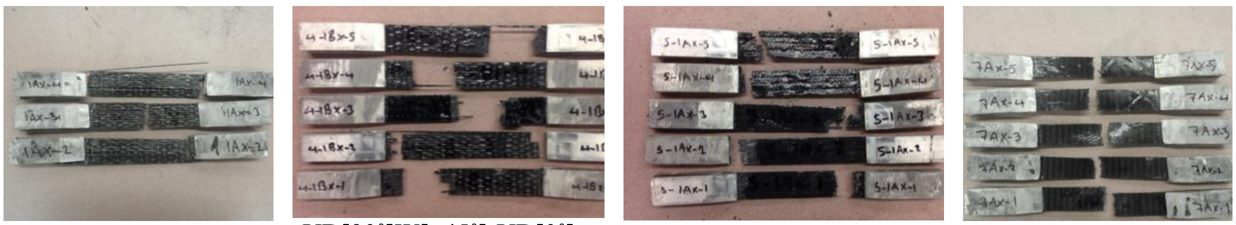
Table: 4 Test results

EXPERIMENT			%Increase in Strength			%Increase in Strain					
Series	**# of Layers**	f_{cc}' (MPa)	$\left(\frac{f'_{cc}}{f_{co}}\right)$	f_l (MPa)	ε_{cc}'	$\left(\frac{\varepsilon'_{cc}}{\varepsilon_{co}}\right)$	ε_1	k_1	μ_{cu}	e_{cu}	w_{cu}
1*	4	177.9	313.4	79.0	0.052	2043.2	0.0180	1.71	2.92	5.96	1.87
	8	263.7	512.7	125.2	0.062	2427.1	0.0240	1.76	2.60	7.59	1.24
2*	4	81.3	88.9	25.1	0.023	849.5	0.0018	1.52	13.07	1.32	9.18
	8	113.8	164.6	50.7	0.035	1328.3	0.0145	1.40	2.45	2.70	1.69
3	4	104.1	141.9	39.7	0.030	1130.2	0.0110	1.54	2.78	2.13	1.91
4	4	43.7	1.02	10.7	0.057	2248.9	0.0077	0.009	5.13	1.47	4.22

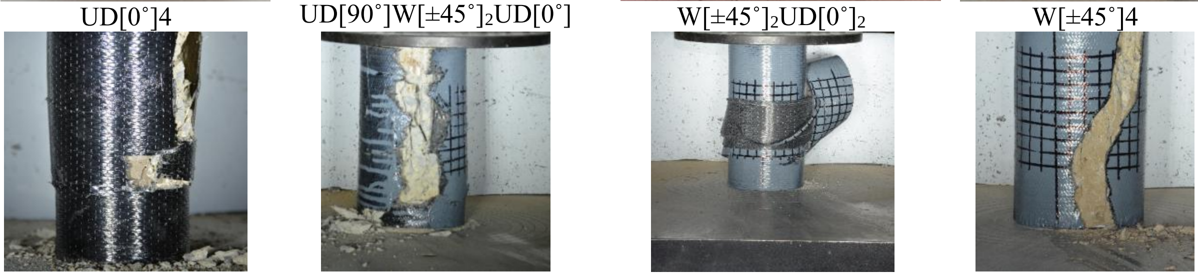
Fiber orientation and stacking sequence also had a significant impact on the failure mode of the CFRP confined concrete cylinders, with more brittle failures observed in the case of specimens with large amount of UD [0˚] fibers and ductile failures in specimens having larger amount of angular fibers. Combination of both fiber types resulted in a hybrid of both responses. As shown in Figure 5 cylinders with purely UD [0°] (fibers aligned in the hoop direction) had brittle and explosive failures, due to the large release of energy as the FRP jacket fails. Cylinders confined with CFRP sheets having fibers aligned in the angular direction had more ductile and gradual failures. The results also show that applying the angular CFRP sheets as an inner layer and the hoop direction sheets in outermost layers as in

Series 3 is one strategy that can prevent catastrophic brittle failures, with concrete crushing in the concrete core confined within the FRP jacket, preventing the violent expulsion of concrete fragments at failure.

In summary, confinement of specimens with unidirectional fibers aligned purely in the hoop direction (UD [0˚]) as in Series 1 resulted in the best overall stress-strain performance at 4 layers, with largest increase in strength, and overall toughness. On the other hand the use of angular fibers in series 4 resulted in increased strain capacity, although the use of this type of CFRP may require a greater amount of layers to achieve satisfactory performance. The response of other series showed a hybrid response due to the combined effect of different fiber orientation, however the response was generally dominated by the influence of the unidirectional hoop fibers. Fiber orientation and stacking sequence also had an effect on failure mode, with greater ductility observed in specimens with FRP with fibers oriented at ±45˚.



UD[0˚]4 UD[90˚]W[±45˚]$_2$UD[0˚] W[±45˚]$_2$UD[0˚]$_2$ W[±45˚]4



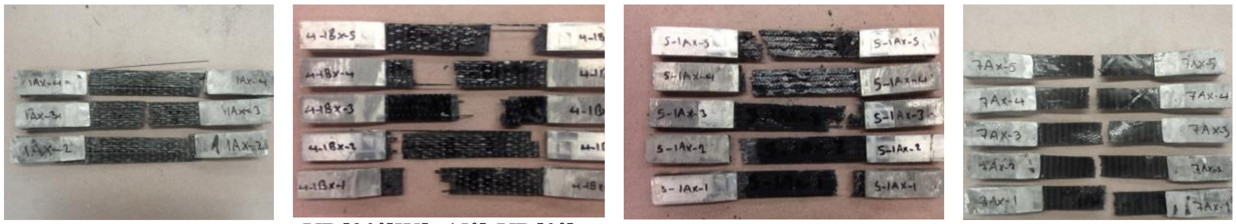
UD[90˚/0˚]$_2$ UD[90˚]W[±45˚]$_2$UD[0˚] W[±45˚]$_2$UD[0˚]$_2$ W[±45˚]$_4$

Figure 5: Post failure photos of coupons and cylinders with different stacking sequences (4 layers)

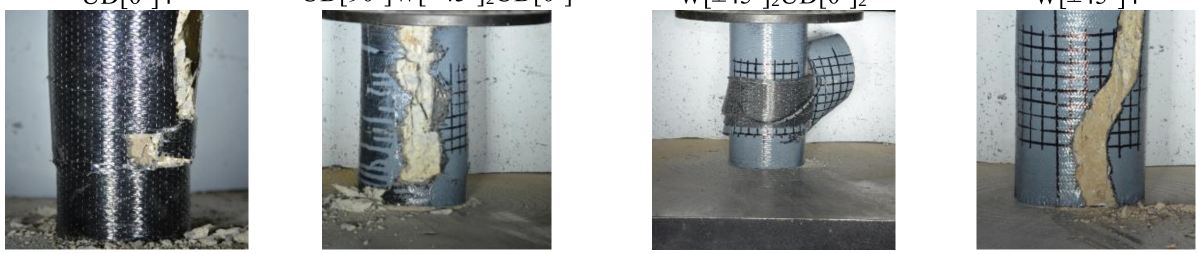
4.3 Effect of number of layers

<u>4.3.1 Series 1 (UD [0˚])</u>

The specimens in Series 1 (UD [0˚]) were confined with 4 and 8 layers of unidirectional CFRP with fibers aligned in the hoop direction. Figure 6 compares the stress-strain response of typical specimens with 4 and 8 layers in this series (UD [0˚]$_4$ and UD [0˚]$_8$). Figure 6 demonstrates that specimens having additional layers exhibiting a larger gain in strength and overall toughness. Cylinders with 4 and 8 plies had average increase in stress (f'_{cc}/f_{co}) of 313% and 512%, respectively. The effect of increasing the number of layers is less important in the case of the increase in strain ($\varepsilon'_{cc}/\varepsilon_{co}$) with average values of 2043% and 2427%, for the same set of specimens. The stress-strain behavior can be further investigated by comparing the strength, ductility and toughness parameters reported in In summary, confinement of specimens with unidirectional fibers aligned purely in the hoop direction (UD [0˚]) as in Series 1 resulted in the best overall stress-strain performance at 4 layers, with largest increase in strength, and overall toughness. On the other hand the use of angular fibers in series 4 resulted in increased strain capacity, although the use of this type of CFRP may require a greater amount of layers to achieve satisfactory performance. The response of other series showed a hybrid response due to the combined effect of different fiber orientation, however the response was generally dominated by the influence of the unidirectional hoop fibers. Fiber orientation and stacking sequence also had an effect on failure mode, with greater ductility observed in specimens with FRP with fibers oriented at ±45˚.



UD[0˚]4 | UD[90˚]W[±45˚]$_2$UD[0˚] | W[±45˚]$_2$UD[0˚]$_2$ | W[±45˚]4

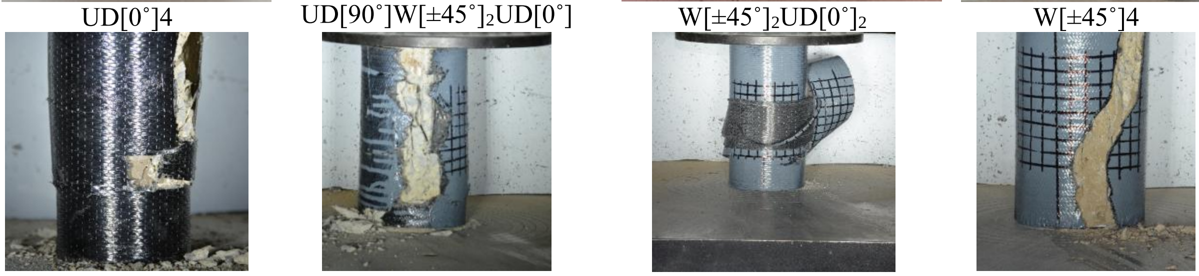


UD[90˚/0˚]$_2$ | UD[90˚]W[±45˚]$_2$UD[0˚] | W[±45˚]$_2$UD[0˚]$_2$ | W[±45˚]$_4$

Figure 5: Post failure photos of coupons and cylinders with different stacking sequences (4 layers)

. The number of plies is found to have an insignificant influence on the strength effectiveness factor (k_1) with values of 1.71 and 1.76 for cylinders with 4 and 8 layers of CFRP. The result indicates that while overall stress increases with additional layers of FRP, the incremental increase in stress is not directly proportional to the number of applied layers (i.e. doubling the number of CFRP layers does not double the peak confined stress). Examination of the data in In summary, confinement of specimens with unidirectional fibers aligned purely in the hoop direction (UD [0˚]) as in Series 1 resulted in the best overall stress-strain performance at 4 layers, with largest increase in strength, and overall toughness. On the other hand the use of angular fibers in series 4 resulted in increased strain capacity, although the use of this type of CFRP may require a greater amount of layers to achieve satisfactory performance. The response of other series showed a hybrid response due to the combined effect of different fiber orientation, however the response was generally dominated by the influence of the unidirectional hoop fibers. Fiber orientation and stacking sequence also had an effect on failure mode, with greater ductility observed in specimens with FRP with fibers oriented at ±45˚.

UD[0˚]4 | UD[90˚]W[±45˚]$_2$UD[0˚] | W[±45˚]$_2$UD[0˚]$_2$ | W[±45˚]4



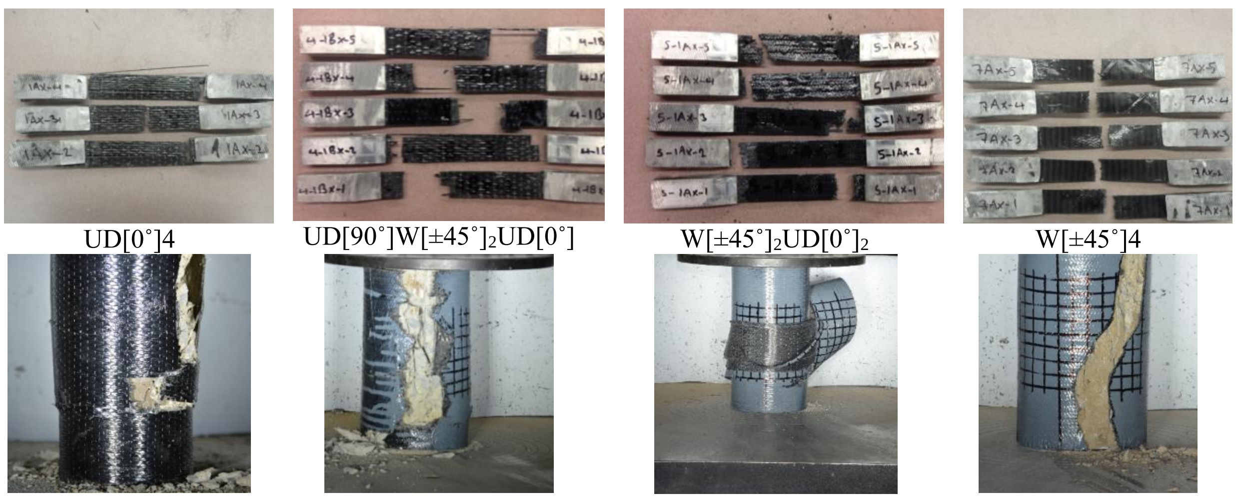
UD[90˚/0˚]$_2$ | UD[90˚]W[±45˚]$_2$UD[0˚] | W[±45˚]$_2$UD[0˚]$_2$ | W[±45˚]$_4$

Figure 5: Post failure photos of coupons and cylinders with different stacking sequences (4 layers)

, shows that the energy absorption capacity (e_{cu}) increases proportionally with the amount of layers. Specimens with 4 and 8 plies of CFRP had average energy absorption capacity factors of 5.9 and 9.7, respectively. The improvement in toughness and ductility due to the increase in CFRP layers is not as obvious when evaluated in terms of work index factor (w_{cu}) or ductility factor (μ_{cu}). Ductility factors (μ_{cu}) of 2.92 and 2.07, as well as work index factors (w_{cu}) of 1.87 and 1.24 were obtained for specimens confined with 4 and 8 layers of CFRP sheets, respectively. The ductility factor decreases with the increase in the number of layers and this can be explained by the fact that strain ε_1 (0.018 to 0.46) increases proportionally to the number of plies, while the associated increase in maximum strain ε_{cc}' (0.052 to 0.062) is relatively small. All specimens in this series failed in a brittle manner, however failures were found to be more explosive for cylinders with a greater CFRP plies (see Figure 6).

4.3.2 Series 2 (UD[90˚]W[±45˚]$_2$UD[0˚])

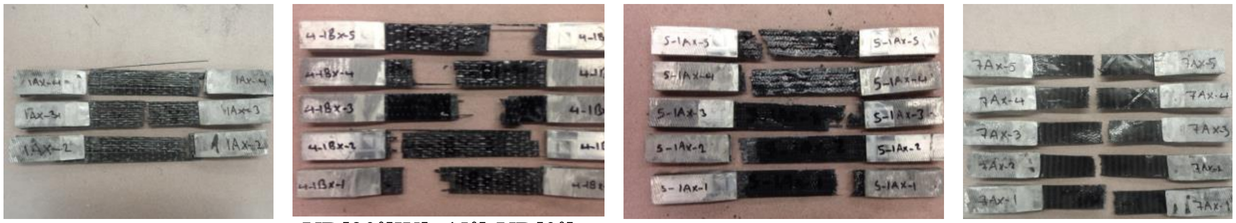
The series 2 specimens (UD[90˚]W[±45˚]$_2$UD[0˚]) had either 4 or 8 plies of CFRP. The stress-strain response of specimens in this series is shown in Figure 7 and the various stress-strain indicators for this series are reported in and In summary, confinement of specimens with unidirectional fibers aligned purely in the hoop direction (UD [0˚]) as in Series 1 resulted in the best overall stress-strain performance at 4 layers, with largest increase in strength, and overall toughness. On the other hand the use of angular fibers in series 4 resulted in increased strain capacity, although the use of this type of CFRP may require a greater amount of layers to achieve satisfactory performance. The response of other series showed a hybrid response due to the combined effect of different fiber orientation, however the response was generally dominated by the influence of the unidirectional hoop fibers. Fiber orientation and stacking sequence also had an effect on failure mode, with greater ductility observed in specimens with FRP with fibers oriented at ±45˚.



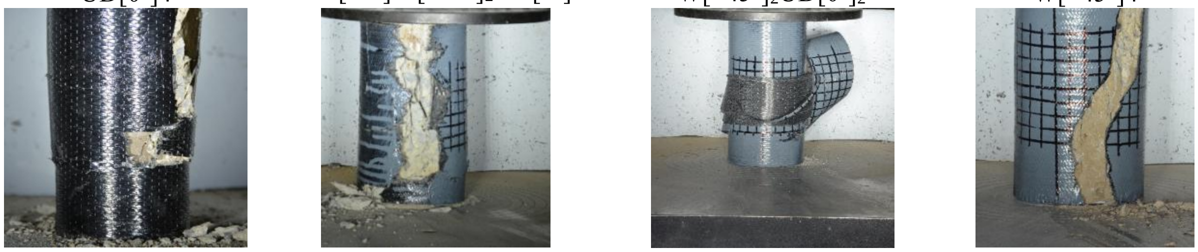
UD[90˚/0˚]$_2$ UD[90˚]W[±45˚]$_2$UD[0˚] W[±45˚]$_2$UD[0˚]$_2$ W[±45˚]$_4$

Figure 5: Post failure photos of coupons and cylinders with different stacking sequences (4 layers)

. Failure photos for typical cylinders in this series are shown in Figure 7. Provision of unidirectional fibers in the hoop direction in this series resulted in some incremental increase in stress. Similarly, provision of woven CFRP with angular fibers led to increase in strain capacity. Cylinders wrapped with 4 layers of CFRP showed enhancement in strength (f_{cc}'/f_{co}) of roughly 88.9%, while an average increase in strain ($\varepsilon_{cc}'/\varepsilon_{co}$) of 849.5%. Specimens with 8 plies showed further increases in strength and strain with average values of 164.6% and 1328.3%. When examining the strength enhancement in terms of the strength effectiveness factor (k_1) the values fluctuate around 1.5, with average values reducing from 1.53 to 1.40 as the number of plies is increased from 4 to 8, an indicator of reduced CFRP efficiency as the number of plies is doubled . The effect of the number of plies is more evident when evaluated in terms of energy absorption capacity (e_{cu}), where average values double from 1.32 to 2.70 when increasing the number of plies from 4 to 8. The opposite effect is observed when comparing the work index (w_{cu}) and ductility factor (μ_{cu}) for these specimens, with a six fold decrease as the number of layers goes from 4 to 8 layers (In summary, confinement of specimens with unidirectional fibers aligned purely in the hoop direction (UD [0˚]) as in Series 1 resulted in the best overall stress-strain performance at 4 layers, with largest increase in strength, and overall toughness. On the other hand the use of angular fibers in series 4 resulted in increased strain capacity, although the use of this type of CFRP may require a greater amount of layers to achieve satisfactory performance. The response of other series showed a hybrid response due to the combined effect of different fiber orientation, however the response was generally dominated by the influence of the unidirectional hoop fibers. Fiber orientation and stacking sequence also had an effect on failure mode, with greater ductility observed in specimens with FRP with fibers oriented at ±45˚.



UD[0˚]4 | UD[90˚]W[±45˚]$_2$UD[0˚] | W[±45˚]$_2$UD[0˚]$_2$ | W[±45˚]4



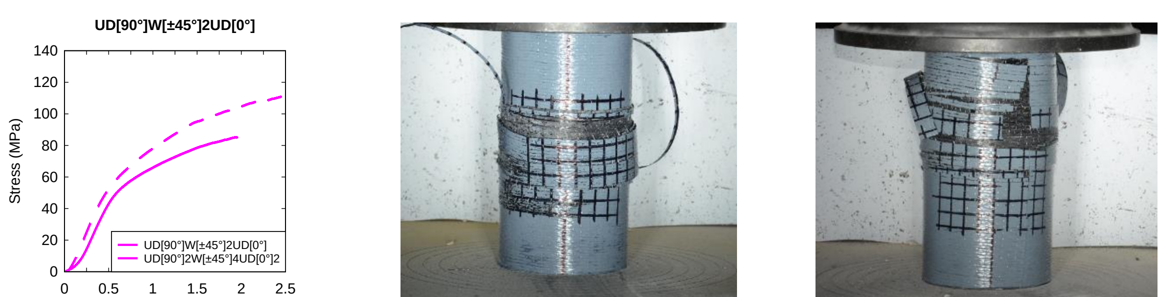
UD[90˚/0˚]$_2$ | UD[90˚]W[±45˚]$_2$UD[0˚] | W[±45˚]$_2$UD[0˚]$_2$ | W[±45˚]$_4$

Figure 5: Post failure photos of coupons and cylinders with different stacking sequences (4 layers)

). As noted before the stress-strain response seems to be dominated by the unidirectional hoop direction fibers, although the transition point between the initial and secondary branches is more rounded (particularly at 8 plies). In terms of failure mode, the specimens showed relatively less explosive failures when compared to specimens in series 1 due to the provision of angular fibers.

a) Stress-Strain Curves | b) 4 layers | c) 8 layers

Figure 6: Stress-strain curve and post failure photos of CFRP confined cylinders, series 1 (100 mm)



a) Stress-Strain Curves | b) 4 layers | c) 8 layers

Figure 7: Stress-strain curve and post failure photos of CFRP confined cylinders (series 2 (100 mm))

5. CONCLUSIONS

The following conclusions can be drawn based on the findings from the cylinder tests:

1. The stress-strain behavior of FRP-confined concrete is strongly influenced by FRP fiber orientation and stacking sequence;
2. Cylinders confined with unidirectional fibers aligned in the hoop direction (UD [0°]) show a bilinear response which has been reported by other researchers, with an initial ascending parabolic branch, followed by a quasi-linear secondary branch with increase in stress and strain until brittle failure of the FRP jacket.
3. Cylinders confined with angular fibers (45°) show a different response, with limited increase in peak stress and significant increase in strain capacity, with a distinct stress-strain plateau after peak stress;
4. In this study it was observed that the stress–strain curves of cylinders with different layup configurations follow the trend of the strongest fibers. For example, in the case of UD[90˚]W[±45˚]$_2$UD[0˚] and W[±45˚]$_2$UD[0˚]$_2$, the curve trend was found to be dominated by the UD[0˚] sheets, although the other fiber orientations modify some aspects of the stress-strain response (e.g. rounding of transition point when 90˚ CFRP sheets are added, and effects on strength, stiffness and strain capacity with 45˚ CFRP sheets);
5. Peak stress and strain capacity of CFRP-confined concrete increases proportionally with the number of CFRP layers, although the efficiency and contribution of additional CFRP sheets reduces once the number of sheets reaches a certain threshold;
6. Brittle fracture of CFRP jackets was experienced in specimens confined with unidirectional fibers aligned in the hoop direction. The failures became more brittle and explosive as the number of UD[0˚] CFRP plies was increased. Specimens confined with angular fibers showed gradual and ductile failures. Specimens confined with layups consisting of multiple fiber orientations, showed a hybrid failure response with failure mode affected by the combination of CFRP orientations as well as sequence of stacking.

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